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Fog-water collection for community use

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A B S T R A C T

Fog is a potential source of water that could be exploited using the innovative technology of fog collection. Naturally, the potential of fog has proven its significance in cloud forests that are thriving from fog interception. Historically, the remains of artificial structures in different countries prove that fog has been collected as an alternative and/or supplementary water source. In the beginning of the 19th century, fog collection was investigated as a potential natural resource. After the mid-1980s, following success in Chile, fog-water collection commenced in a number of developing countries. Most of these countries are located in arid and semi-arid regions with topographic and climatic conditions that favour fog-water collection. This paper reviews the technology of fog collection with initial background information on natural fog collection and its historical development. It reviews the climatic and topographic features that dictate fog formation (mainly advection and orographic) and the innovative technology to collect it, focusing on the amount collected, the quality of fog water, and the impact of the technology on the livelihoods of beneficiary communities. By and large, the technology described is simple, cost-effective, and energy-free. However, fog-water collection has disadvantages in that it is seasonal, localised, and the technology needs continual maintenance. Based on the experience in several countries, the sustainability of the technology could be guaranteed if technical, economic, social, and management factors are addressed during its planning and implementation.

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1. Introduction

Availability of adequate and sustainable water resources is one of the most important factors in household livelihood improvement and economic development. In general, challenges exist in supplying adequate and sustainable fresh water. Demand for water is increasing due to population growth, expansion of agricultural areas, and rising industrial demand; existing conventional water sources are being depleted and polluted by industrial, agricultural, and domestic effluent, and other human activities. The problem is exacerbated in regions with low precipitation and droughts: developing countries in arid and semi-arid regions are most vulnerable and highly affected by water scarcity. In such regions, there is a need to explore potential alternative water resources that are economically feasible and renewable [1].

Fog is a potential source of water that could be exploited using the innovative technology of fog collection. This paper reviews this technology, starting with background information on natural fog-water collection and its historical development (Sections 2 and 3). It describes the climatic and topographic features that dictate fog formation and innovative technologies to collect fog, identifying climatic and topographic combinations most favourable to the effective functioning of these technologies (Sections 4 and 5). The paper reviews the wealth of experience gained in fog-water collection by different countries, with special emphasis on the amount of fog water collected, the quality of fog water, and the impact of the technology on livelihoods in the beneficiary communities. In addition, the paper discusses advantages and disadvantages of the technology as well as factors that dictate its sustainability (Section 6). Finally, based on experience in several countries, we draw conclusions and recommendations for future consideration of the technology (Section 7).

2. Natural fog collection

Fog interception is a natural phenomenon that enables trees in fog-prone areas to collect water from the atmosphere and safeguard their existence even in water-scarce situations. Intercepted fog water contributes a significant proportion of the hydrological input in some coastal dry lands [2]. For example, on the American Pacific Coast, tall coniferous forests (redwoods) naturally thrive because of the additional fog water they intercept. In these areas, the rainfall is sufficient only to support Mediterranean scrub vegetation [3]. Similarly, in the northern coastal hills of Chile and Peru, where rainfall is nearly absent, a particular type of forest grove ("loma") survives almost exclusively from advective sea fog [4].

Over the years, a number of studies have been undertaken to understand fog interception by trees. Kerfoot [5] and Schemenauer [2] have reviewed previous studies. The studies revealed that fog precipitation is a localised phenomenon, largely restricted to slopes and summits of mountainous regions where onshore maritime air is modified by orographic influences. Trees are good fog collectors and their efficiency depends on their height and leaf structure. Naturally, the taller vegetation with small needle-like leaf structures such as coniferous trees tends to intercept more fog. The intensity of fog interception also varies with horizontal wind speed and the size and distribution of water droplets [6]. Fog composed of mainly large droplets results in rapid deposition of water. Thus, where fog is frequent, windblown fog droplets are collected by vegetation in enormous quantities, large drops coalescence on foliage and ultimately drop to the ground. Fog precipitation would probably be of greater significance in tropical areas where the water content of the atmosphere is usually greater. The hydrological importance of fog to many coastal and montane eco-systems is well understood, but a reliable method to quantify fog deposition on cloud-forests that is also convenient and inexpensive is not available [7].

Similarly, the information relating to how animals and plants obtain atmospheric water in a hyperarid environment where rainfall is extremely rare has been reviewed by Henschel and Seely [8]. It was suggested that fog may be collected using tilted surfaces that have alternating hydrophobic, wax-coated, and hydrophilic, non-waxy regions [9]. This type of surface was found to occur on the wings of Namib Desert beetles that survive by collecting early-morning fog water. More recent research in a laboratory however has shown that the fog-basking behaviour of the beetle itself is more important than the surface structural properties of its wings, in the collection of water from fog [10].

In their review, Henschel and Seely [8] concluded that further research on ecophysiological mechanisms could improve applications of fog- and dew-water capture. They also suggested investigation into cost-effective methods that use osmotic pressure, or extremely fine hydrophilic structures coupled with pumps to obtain water from unsaturated air.

3. History of fog collection

A number of fog- and dew-water collection methods have been documented earlier that were mainly practiced in arid and semi-arid areas. These methods included both direct utilisation of fog water that dripped under trees or construction of artificial mound-like structures to intercept fog and dew. Fog water which is naturally intercepted by tree leaves from intense fog has been used as a source of potable water for many years in different areas. For example, inhabitants of the Canary Islands for centuries used "fountain" trees (laurels, junipers, pine trees) as their sole source of drinking water for both human and animals [11]. Also, inhabitants of the mountains in Oman built cisterns under trees to collect fog water for domestic use [12].

In other areas, fog-water collection efforts were augmented by artificial structures. Remains of artificial structures used to collect fog and dew were found in desert areas of the Mediterranean region and South America [13]. In the Atacama Desert, a pile of stones was used to cool and condense water droplets inside a cavity occupied by a warm moist air mass during the daytime. During night-time these structures were used to condense dew which was then channelled and collected in the cavity. Likewise, stone piles built for the same purpose of dew collection have been found on the Crimean Peninsula [14,15]. In ancient Palestine, small low circular honeycombed walls were constructed around vines, so that dew and mist could precipitate on the plants [13]. Lightfoot [16] has investigated, in depth, these techniques of improving ground water for agricultural purposes through water condensation on stones.

The scientific interest to study and measure fog as a natural resource started in South Africa (table mountain) at the beginning of the 1900s [16]. During this period, scientists tried to measure the volume of fog water intercepted by vegetation using two rain gauges. The two rain gauges were set differently: one was left in the open as a normal rain gauge while reeds were suspended above the second one. This method then became a standard practice for measuring fog precipitation before the introduction of the Standard Fog Collector (SFC) by Schemenauer and Cereceda [17]. In 1969, the pioneer fog collection project was implemented in South Africa. The main aim was to provide a temporary water supply for Air Force personnel operating in the Mpumalanga area. The fog collector consisted of two large fog plastic screens (each 28 m long by 3.6 m high) erected perpendicular to prevailing wind. An average of 31 m^3 of water was collected per month (about 11 $L\,m^{-2}\,day^{-1}$) between the period of October 1969 and December 1970 [18].

In 1987, the second largest operational fog-water collection project was implemented at the small fishing village of Chungungo in northern Chile, by researchers at the National Catholic University of Chile and the International Development Research Centre in Canada [19]. A total of 100 fog collectors (each 12 m long by 4 m high) were erected on a hill overlooking the village. According to reports, production rates varied from zero on clear days to a maximum of 20 $L\,m^{-2}\,day^{-1}$. With this arrangement, each of the 300 villagers received about 33°L of clean water per person per day [12,20]. As a result of these successes, similar fog collection projects have been initiated (Fig. 1) and implemented in many parts of the world (see Section 6).

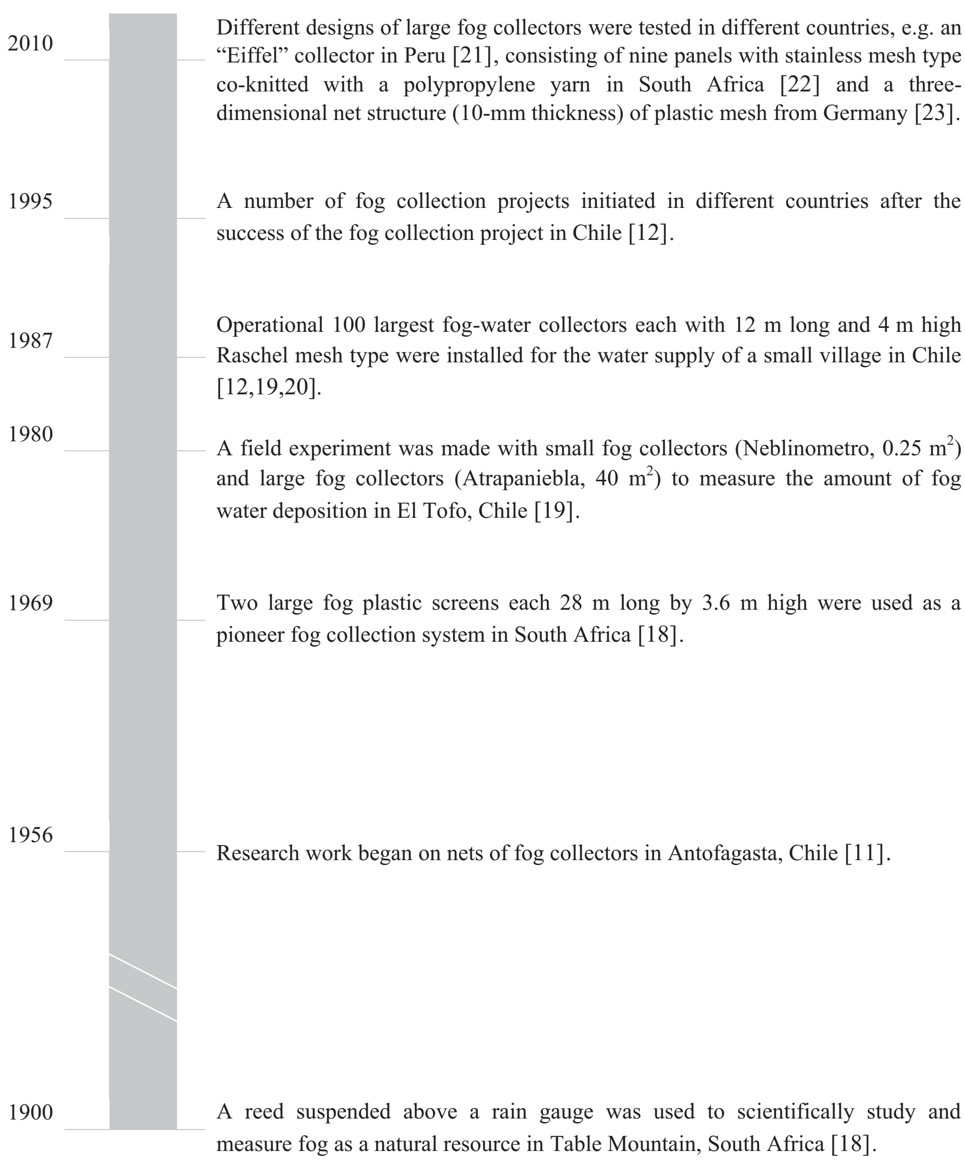

Fig. 1. Timeline of the major developments in fog-water collection technology.

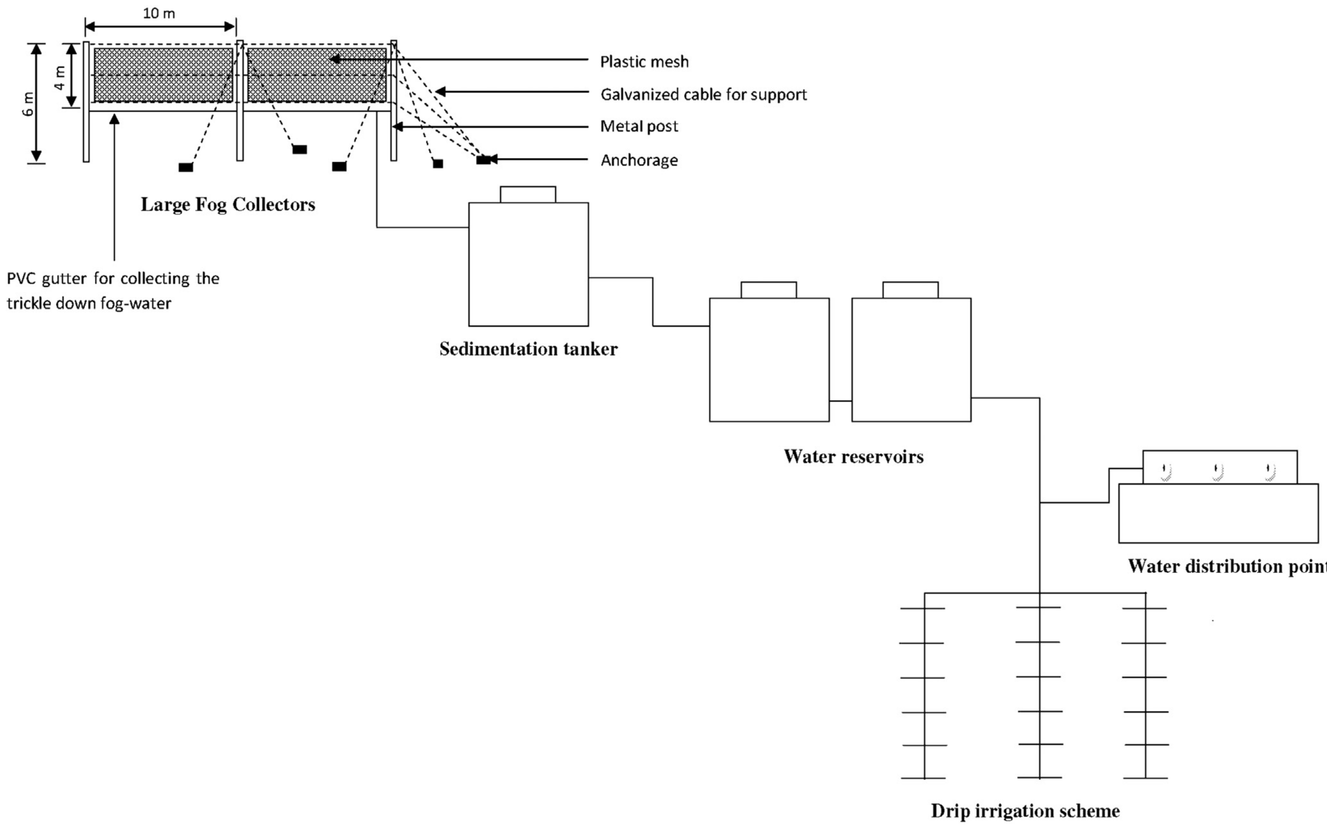

Fig. 2. Large fog collectors are installed at selected elevated sites facing the prevailing wind direction. During a fog period, a fraction of the fog droplets are intercepted as near-saturated air passes through a plastic mesh. The minute fog droplets coalesce to form larger water droplets that trickle down the mesh fabric into an attached PVC gutter. The collected water can then be gravity-fed to a sedimentation tank to settle its suspensions and finally flow to a domestic water supply and/or irrigation system.

4. Climatic and topographical conditions for fog formation

By definition, fog is a cloud that touches the ground surface; for practical purposes, meteorologists use the measurement of visibility to differentiate between fog and other climatic elements such as mist and haze. Fog reduces visibility to less than 1000 m. A visibility of less than 2000 m but greater than 999 m is considered to be mist if the relative humidity is greater than 95%, but if less than 95% it is described as haze [21–24]. Similarly, fog droplet diameter varies markedly and ranges between around 1 μm to 40 μm. The droplet diameters of rain range from 0.5 mm to 5 mm. For drizzle, diameters range from 40 μm to 0.5 mm [12].

Naturally, fog is formed through cooling of air to below its dew point (producing advection and radiation fog) or by adding water vapour and thereby increasing the dew point (producing steam fog or frontal fog). In principle, air at a given temperature can contain only a certain amount of water vapour. This amount increases as the air temperature increases, and decreases as the air temperature decreases. Therefore, if the air temperature of a saturated air mass decreases, the excess water vapour from the air condenses to form fog. Generally, there are seven types of fog that can be distinguished [7]. Four are named according to the location and process of fog formation (radiation fog, sea fog, steam fog, advection fog) and the rest are based on the geographical terms, irrespective of where and how they were formed (coastal fog, valley fog, orographic fog). Only the most common fog types (advection and orographic fog) which are also dominant in the eastern escarpment of Eritrea are described here.

Advection fog occurs when a moist air mass passes over a cool surface by advection (horizontal wind) and is cooled. It is most common at sea when tropical air encounters cooler waters, including areas of cold-water upwelling. A cold front can transport the marine layer coastward, an occurrence most typical in the spring or late autumn. During the summer months, a low pressure trough is produced by intense inland heating that creates a strong horizontal pressure gradient, drawing in the dense marine layer [25]. Orographic fog is formed during uphill transport and adiabatic cooling of humid air masses. Oceans are major sources of water vapour so that the combination of an ocean with a near-coast mountainous region is a favourable setting for collecting fog water [25].

Schemenauer et al. [19] described four major regional-scale topographic features within a given favourable macro-topography that dictate the flow of air from oceans to continents. These four aspects of relief firstly include a high mountain range for maximum fog interception. Secondly, the principal axis of the mountain range should face perpendicular to the prevailing wind direction at the altitude of the fog. Thirdly, the potential mountain range should be within close proximity of a coastline in order to minimise the loss of cloud water due to evaporation. There should also be a broad basin on the leeward side of the mountain range to create a horizontal air pressure gradient to force oceanic air through the mountains. Also, in addition to these four features it is preferable if the broad basin is found through a natural path of a saddle point.

5. The technology of fog collection

The technology of fog collection is an innovative method whereby fog droplets, which are carried by wind, are collected through a simple surface impaction process. Physically, a plastic mesh is stretched facing the prevailing wind direction and thus part of the fog droplets are intercepted as the air passes through the mesh. Minute fog droplets coalesce and form larger water droplets on the mesh fabric and trickle down into an attached

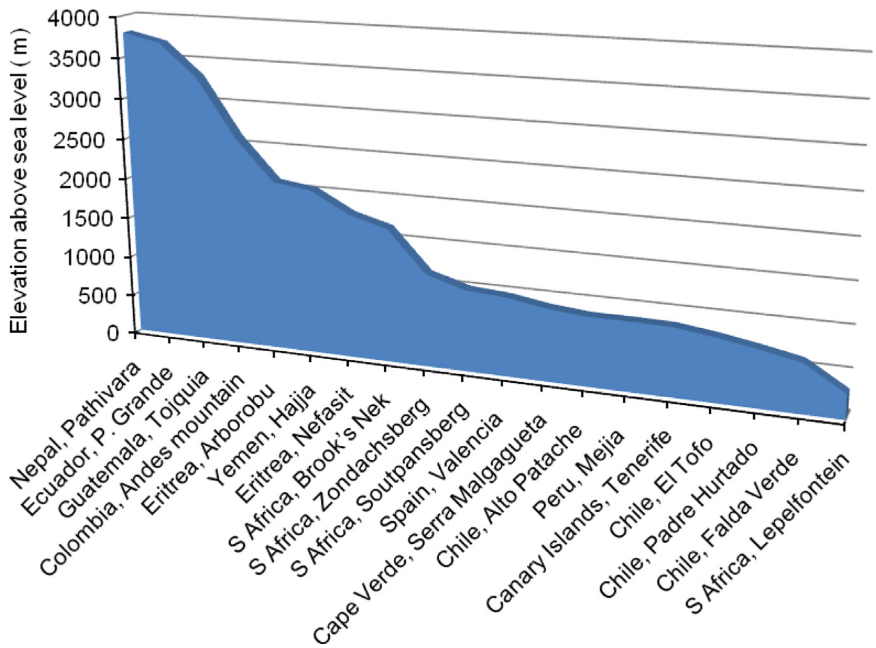

Fig. 3. Fog-water collection locations and their elevation in metres above sea level.

gutter. The collected water can then flow to a sedimentation tank through gravity, and ultimately to a domestic water supply and/or irrigation system (Fig. 2).

Dominantly, the mesh type that is used in different countries is polypropylene or polyethylene mesh with a shading coefficient of 35%. The mesh is woven in a triangular pattern with a flat fibre about 1 mm wide and 0.1 mm thick to have a pore size of about 10 mm. Schemenauer and Joe [26] found out that fibre width has a direct effect in collecting fog droplets. This means the ten 1-mm wide ribbons generate more water than a 10-mm wide ribbon. Usually a double layer of mesh is used to cover 70% of the surface area of the collector, depending on how the fibres overlap. This, in turn, facilitates run-off of the collected water as the two layers move against each other. In different countries, various mesh materials have been tested to suit the local situation [27]. In South Africa, a more robust material made up of a co-knit of stainless steel and polypropylene yarn has been tested and found more appropriate. The stainless steel gives strength and the yarn increases efficiency as a collector [22].

A potential project site is selected through initial collection of important geographical information such as altitude, distance from sea, relief, and slope orientation using the following methods: cartographic analysis, geographical information systems, remote sensing analysis, and a preliminary field assessment [28]. Once a potential project site is identified, a feasibility study needs to be undertaken to measure daily fog-water collection.

Measurement of the precipitation rate is relatively easy if the precipitation is in the form of rainfall. Generally, a tipping bucket rain gauge is used for this purpose. Various methods used to measure light rain, drizzle, and heavy fog have been reviewed [29]. A commercially-available total precipitation unit (YES Inc., Turners Falls, Maryland, USA) contains a sensor head of two isolated plates that are warmed to measure the rate of precipitation by how much power is needed to evaporate the precipitation on the upper plate while keeping the plate surface temperature constant. The influence of wind is removed using measurements from a second plate, heated to the same temperature, directly under the first plate. Precipitation rate systems usually require a source of electrical power due to their high power consumption (typically 100–600 W) and have a measurement resolution that may be inadequate for short-term measurements of water collection – typically 0.1 mm h^{-1} – and an accuracy of around 0.5 mm h^{-1}.

However, the fog and dew rates are much lower and very difficult to measure. Standard fog collectors (SFC) have been used to measure fog using intercepting material such as nylon mesh. The SFC is a 1 m^2 frame with a double layer of 35% shade cloth mesh mounted perpendicular to the prevailing wind direction [17]. The frame is mounted so that its base is 2 m above ground. The total volume of collected water is measured using a tipping bucket gauge and a data logger. If a second tipping bucket rain gauge is used to measure the rainfall, the fog amount can be estimated from the difference between the two rain gauge measurements. If the SFC yields significant fog-water collection, the next step is to install a large fog collector (LFC). The principle is identical to that of SFC but a larger mesh (10 m long by 4 m high) is stretched by cables over two posts [12]. At the lower edge of the mesh, a gutter is attached usually 2 m above the ground in order to increase the collection efficiency. The efficiency of fog collection rate is strongly dependent on both the wind speed and the fog droplet size. On the whole, the collector efficiency is roughly 20% for an incoming fog with efficiencies decreasing away from the centre of the mesh [26].

6. Experience gained from fog collection

Over the last few decades, different countries considered fog a viable unconventional water source and its potential has been extensively studied to alleviate shortages of water for domestic, small-scale agricultural, and reforestation purposes. The countries that have tested the technology of fog collection are described along with achieved results, impact, sustainability factors, advantage, and disadvantage of the technology.

6.1. Countries that have tested the technology

Countries that have installed and evaluated the potential of fog-collection technology are mostly developing countries. These countries

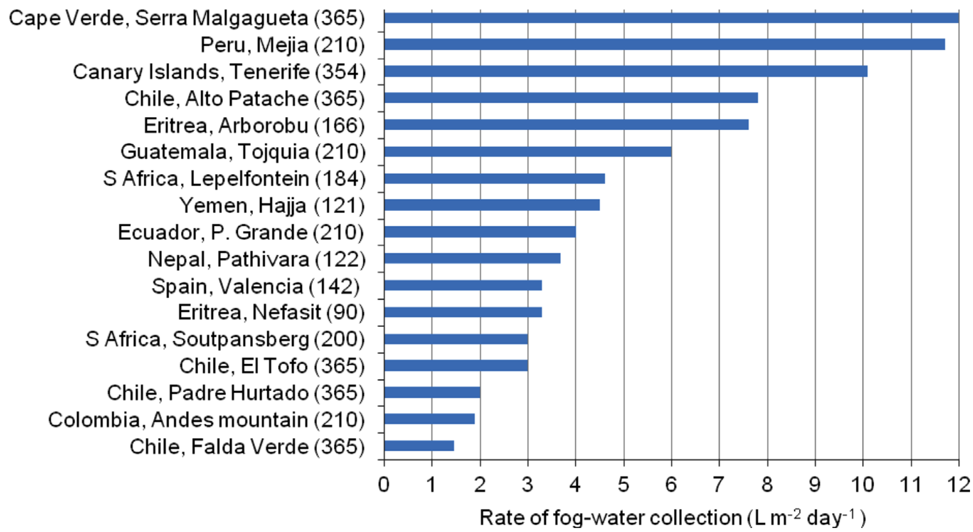

Fig. 4. Rate of fog collected (L m^{-2} day^{-1}) for the countries that utilised the technology of fog collection. The average number of fog days per year is indicated in brackets.

do not have the means to extend a conventional water supply system to all parts of their country. In addition, almost all of these countries are located in arid and semi-arid regions of the world where there is a shortage of potable water. According to Klemm et al. [23], these countries include the driest part of the western coast of South America (Chile, Peru, Ecuador, and Colombia), the arid west coast of southern Africa (South Africa and Namibia), the Sub-Sahara region of East Africa (Eritrea and central Tanzania), the dry region of the Arabian Peninsula (Oman, Yemen, and Saudi Arabia), the dry part of the northwest coast of Africa (Morocco), and the Mediterranean semi-arid area (Spain) and areas in southern Europe (Croatia) that have acute water resource problems due to hot and dry summer conditions, and mild and wet winters coupled with strong water demand for domestic, agricultural, and industrial uses. Many of these regions have an adjacent cool ocean current with an arid/semi-arid and/or Mediterranean climate with increased fog-rate collection at higher elevations.

These countries have adopted the technology of fog collection since they have a natural favourable climatic and topographic setting for potential fog formation. Almost all of these countries have high-altitude mountains usually more than 500 m above sea level within close proximity of their coastlines, with the exception of Nepal (Fig. 3). As a result, these mountain ranges are predominantly influenced by coastline climate and usually with summits covered by advection and/or orographic fog types for much of the year. For example, in Chile, the northern part of the western coast is covered by fog almost every day [19,30]. In Colombia, the respective period is 210 days [31], in Peru 210 days [32], in Spain 142 days [33] and in Eritrea 166 days per year. These massive fog occurrences in the mountain ranges for extensive periods have encouraged these countries to consider fog as an alternative water source, using fog collection technology to address their shortage of water.

6.2. Relevance of fog collection

Almost all of the countries that have used fog collection technology are located in dry tropical and subtropical climates. The annual rainfall in many areas of these countries is very low. As a result, many of their communities face a shortage of water outside of their scanty rainy season and in some cases year round. Surface and/or fresh water sources are not a sustainable option due to limited amounts of rainfall. Furthermore, most of these areas are found in an elevated topography and thus the implementation of a conventional water supply system is difficult in practical terms and uneconomical. Therefore, availability of a reliable, renewable, and economically feasible water resource becomes a major challenge to many of these areas.

For years, the inhabitants of these areas were forced to use water resources that are physically and economically demanding to access for a household. For example, in the northern coast of Chile, water is purchased and transported by truck from a source 60 km away. In most countries like Eritrea, Peru, Guatemala, and Nepal, mainly women fetch water from open and unhygienic water sources by carrying it on their back over long distances and undulating terrain [23]. Usually, the amount of water that they fetch per day is minimal and barely sufficient for their daily per capita demand for drinking and cooking without leaving much for their personal hygiene.

However, these areas are bestowed with a natural resource and fog for considerable periods of the year due to their geographical location and climatic condition. Therefore, taking into account the above-mentioned realities, fog collection becomes a relevant practical option for these dry regions to alleviate shortages of water. Over the last few decades, a number of fog collection projects have been implemented in many countries and have demonstrated their viability for domestic, agricultural, and reforestation purposes.

6.3. Major results and impacts of fog collection

The technology of fog collection has been used mainly to improve the shortages of potable water in dry regions of the world (Fig. 4). The first community which benefited from this technology is located in the coastal desert of Chile (Chungungo). The water supply system from fog collection yielded an impressive result and became practical proof of the technology's success. The system was operational from 1989 to 2000, each day producing an average of 15,000 L of potable tap water for all 300 individuals in the village from 100 LFC units. As a result, the living conditions of the community improved. The project also led to the initiation of small-scale agriculture (vegetable gardens and fruit trees) that diversified their diets. Similarly, electricity and tourism started to appear in the village [34]. It also reversed the migration to cities, and population increased from 300 to over 600 permanent residents [35]. Currently, the fog-water supply is not functional because of growing demand – which makes it necessary to find an alternative conventional water supply to serve the increasing population.

Table 1
Current status of operational Large Fog Collectors (LFC) implemented worldwide.

Countries	Site	Operational years	No. of LFCs	Purpose	Current status	Reason for success, continuation, or termination	Sources
Canary Islands	Tenerife (Anaga)	2000–2010*	4	Research on the characteristics of fog and its interaction with vegetation	Operational	Interest in the study of fog characteristics on the island of Tenerife	[53]
Cape Verde	Serra Malgagueta	2003		Community water supply	Not operational	Insufficient involvement of the communities and not enough support given by official service	[54]
Chile	El Tofo (Chungungo)	1987–2002	100	Community water supply	Not operational	Local politics prevented upgrade to support the conventional water supply system	[20,55]
	Alto Patache	1997–2010*	2	Ecosystem and climate research	Operational	Interest for scientific purposes. Also, fog-water collected is used for greenhouse crops	[20,56]
	Padre Hurtado	1999–2004	10	Community water supply	Not operational	The church terminated staff appointments and operation of the sanctuary	[32]
	Falda Verde	2001–2010*	10	Grow *Aloe Vera*	Operational	Strong involvement and commitment by fishermen	[20]
Colombia	Andes Mountain	2008–2010*	1	Rural water supply, environmental education and social reintegration	Operational	Full involvement of the community, both in the experimental and operational stages	[31]
Ecuador	Pachamama Grande	1995–1997	40	Community water supply	Not operational	Lack of technical skills and involvement by local partners	[57]
Eritrea	Arborobu	2005–2010*	10	Community water supply	Operational	Strong will of the zonal and local administration to set it as operational model	[58]
	Nefasit	2005–2009	10	Community water supply	Not operational	Mesh damage, insufficient commitment by the school and community at large since new conventional water supply installed	
Guatemala	Tojquia	2006–2010*	35	Community water supply	Operational	Strong community involvement	[36,59]
Nepal	Pathivara Temple	2001–2010*	2	Water supply for the temple	Operational	Addressed the strong need of the temple for sufficient water	[60]
Peru	Mejia	1995–1999	20	Research on rehabilitation of the lomas ecosystem by fog water	Project completed	Fulfilled the main objectives of the research project (verifying the possibility of rehabilitation of the lomas ecosystem through reforestation supported by fog water)	[32]
South Africa	Lepelfontein	1999–2001	1	Water supply for school	Not operational	Poor maintenance and gale force winds led to failure of the system	[22,1,61,62]
	Soutpansberg	2001–2008	7	Water supply for school	Not fully operational	Lack of required maintenance by recipients and strong wind	[18,48,1]
	Brook's Nek (Eastern Cape)	2010*	3-panel system**	Research to test a new design for fog-water collection	Operational	The preliminary result indicates the system is stable and resistant to strong wind. It has a mesh made up of co-knit stainless steel and polypropylene yarn	[22]
	Lamberts and Doring Bay (West Coast)	2010*	9-panel system				
	Zondachsberg	2010*	3-panel system				
Spain	Valencia	2007–2010*	1	To irrigate 620 one-year-old seedlings of *Pinus pinaster* and *Quercus ilex*	Project completed	Very successful for two years following which the adjacent trees grew tall and were able to collect by themselves	[33,52]
Yemen	Hajja	2003–2005	25	Community water supply	Not operational	Lack of maintenance; use of a non-standard mesh and strong wind	[43,45]

* Projects still in operation when data for this publication were collected and analysed.
** A new design comprises three 40 m^2 panels joined together to form the sides of an equilateral triangle. Four such triangles are linked together to form a nine-panel system.

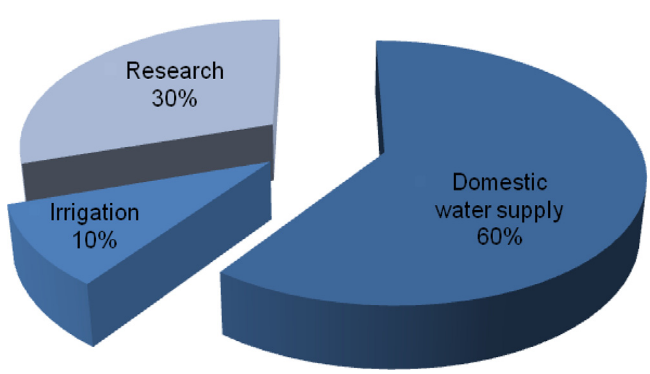

Fig. 5. Percentage of global fog-water utilisation for domestic water supply, research, and irrigation.

After this success and wide media coverage, a number of fog-water supply projects have been initiated worldwide. Currently, there are many operational projects in different countries (Table 1) that serve a whole community and in some cases localised schools like Soutpansberg in South Africa, and Arborobu and Nefasit in Eritrea. Recently, in Guatemala, a family water supply system was introduced and found to be a successful mode of implementation that guarantees sustainability since it creates a strong sense of ownership. The project provided 800 L of water per day to two families and there is high interest from the entire community of 300 people to adopt the technology at a family level [36]. Generally, communities benefit from such water supply projects, and women in particular obtain relief from their routine and laborious daily activity of fetching water. This also allows women to have enough time to participate in relevant food security activities to improve the livelihood of their families. Equally, students involved with such a project have access to clean potable water and are able to cultivate small-scale gardens as an extra-curricular activity within their school compound.

In addition to these implemented projects, a number of research-oriented projects were undertaken in different countries to study the potential of fog-water collection, using SFC units.

Table 2
Total cost for implementation of two independent fog-water supply systems in Eritrea.

Items	Unit	Number of units	Total cost (USD)
Establishment of 20 LFC units	m^2	900	28,193
PVC pipeline system	km	1.2	14,762
Water tankers and distribution system	m^3	30	14,278
Training of water committee (five members)	LS	1	1200
Implementation (personnel and transportation)			5485
Total (USD)			**63,918**
Number of direct beneficiaries			**3045**
Cost per beneficiary			**21**

(*Source*: Vision Eritrea financial report, [58]).

These assessments showed viable daily fog collection rates of 30 L m^{-2} in Oman [37–39], 7.1 L m^{-2} in Morocco [40], 6.2 L m^{-2} in Saudi Arabia [41,42], 5.5 L m^{-2} in Haiti [32], 4.5 L m^{-2} in Yemen [43], 3.3 L m^{-2} in Croatia [44], 2.51 L m^{-2} in Dominican Republic [45] and 1 L m^{-2} in Namibia [46].

In terms of a potential water supply system, fog-water quality is as important as the rate of fog collection in determining the feasibility of a location. The quality of fog water depends primarily on the composition of the incoming fog, the material of collectors, and the chemical composition of dry deposition on collectors that change with the period between fog episodes [47]. A rigorous water quality test could be made by taking representative samples of water from an LFC or samples could be taken from water storage. In most cases, water quality tests are done using the first sampling option using water from the LFC. A water quality test could also be conducted by taking representative samples from the air using a specialised sampler before fog strikes a mesh.

In general, the results achieved in different countries reveal that fog-water samples meet the respective national and World Health Organisation (WHO) standards for water quality. For example, at the El Tofo site in Chile, water quality analyses were done on incoming fog in the air as well as on water from LFC units. Results indicated that the water quality in both cases met the WHO standards for ions and for 23 heavy metals with a slightly lower pH value (about 4), which would not be a problem for domestic and agricultural use [17]. In South Africa, an acceptable high fog-water quality was reported for the villages of Lepelfontein and Soutpansberg [48,1]. In the Namib Desert (Gobabeb), the water quality was found to be within the WHO limits and thus the fog water was recommended as a potential water source to provide clean water for the coastal desert region of south-western Africa [49]. Similarly, in Eritrea, water samples taken from the water supply systems of a school in Arborobu and Nefasit villages showed water quality that met the WHO standards. As part of the water supply management, filtration and chlorination procedures should be employed to preserve the quality of water in storage. In addition, after every dry period, the initial fog water collected needs to be flushed out to exclude debris such as dust and bird droppings that collected in the plastic meshes.

Fog water collection is also being used to drip-irrigate plants for domestic, commercial, and reforestation of degraded forest areas (Fig. 5). Over the last nine years, ten LFC units have been used by local fishermen in Falda Verde, Chile, to drip-irrigate a commercial plant of *Aloe Vera* for supplementary income [50]. Similarly, in a reforestation project, a total of 620 one-year old seedlings of *Pinus pinaster* and *Quercus ilex* trees were drip-irrigated for two years in the Valencia region of Spain, after which the trees were able to collect fog water by themselves [51,52].

6.4. Sustainability factors

The natural resource of fog being utilised to alleviate the problem of insufficient water with innovative technology seems a success story since the inception of the idea. The technology works in areas where conventional water supply is not feasible and the rate of fog-water collection is adequate for much of the year. In order to guarantee the success, the main sustainability factors (technical, economic, social, and management) need to be addressed before installation of the technology. True sustainability is attained when beneficiary communities take full responsibility of managing and operating their own fog-water collection system, as shown in Table 1.

6.4.1. Technical

Even though the technology of fog collection was introduced in most of the countries through foreign assistance, its technical implementation and operation could easily be adopted by local technicians. To that effect, the beneficiary communities need to accept the technology as a viable option compared to conventional means, and then fully participate during planning, implementation, and completion of project, to fully understand and develop a sense of ownership. Overall, community motivation needs to be strong to regularly maintain and closely follow up the system during operation. Strategically, technicians need to be selected from the community and receive hands-on training during implementation of the system. After the project is handed over to the beneficiary community, these trained technicians should be responsible for follow-up and maintenance of the system and the communities should compensate them for their services.

In some countries like Ecuador, Eritrea, Guatemala, Nepal, South Africa, and Yemen, it was observed that there are technological challenges due to large-scale mesh damage owing to strong wind. The physical damage coupled with a lack of community commitment to mend the mesh in time ultimately jeopardised operation of the technology. To alleviate the problem, a number of studies have been undertaken in different countries e.g., [37–39,63,64] to manufacture a robust mesh type that could withstand harsh environments.

6.4.2. Economical

The technology of fog collection is a low-cost technique (Table 2), which does not need electrical power and has low operational costs compared to conventional water supply systems that incur large initial investment and operational costs for fuel, spare parts and high maintenance. Fog-water collection has been implemented in many developing countries through financial aid from international organisations since communities lack the financial means and technical knowledge. In Chile (Chungungo), the initial installation cost for establishment of 60 LFC units along with a 6.2-km pipeline and 100 m^3 storage tankers was USD 37,000 [19]. In Eritrea, the cost incurred for establishment of the two water supply systems in Arborobu (1827 community, students, and teachers) and Nefasit (1218 students and teachers) was USD 63,918. Generally, the cost of 100 LFC units, which would be suitable for a village, is estimated to be about USD 40,000 but the cost might vary depending on site access and length of pipelines where water has to be delivered for use [12].

Once the technology is installed properly, the product lifespan of the polypropylene mesh type is expected to be ten years [28]. While the technology intermittently needs minor maintenance, the associated running costs are minimal and could be managed by the respective beneficiary community. Communities usually introduce a water tariff system to raise funds to cover the running costs, maintenance, and future minor repairs of the system. The

experience of Peru (Lima) and Chile (Chungungo) could be mentioned as a practical example where the communities have established a water committee to collect money and administer the system. These two countries used two different reimbursement systems. In Lima, fog water was sold at a reasonable price compared to truck-delivered water with money collected daily directly from users. In Chungungo, a water metre installed in each house enabled monthly billing [12].

6.4.3. Social

it has been demonstrated that communities with high motivation and a strong sense of ownership could sustainably operate their own water supply system (Table 1). Different countries have acknowledged that parallel with physical installation of the technology, sensitisation and awareness activities need to be undertaken to create a social acceptance as well as motivate beneficiary communities to have a strong sense of ownership. Particularly, women need to be involved starting from planning to the implementation stage as they are the primary users and direct beneficiaries of the collected water.

6.4.4. Management

In most cases, water committees are established from the beneficiary community to manage their respective fog-water collection system. These volunteer members need to be strongly motivated and develop a strong attachment to run their water supply system. Usually they hire trained local technicians and tariff collectors from users. In addition, there should always be a local institution – governmental or local non-governmental organisation – that assists and looks after performance of the water committee and gives regular technical assistance until the beneficiaries fully adopt the technology and are able to efficiently and independently run the system.

6.5. Technological advantages

Generally, this technology is feasible in areas where conventional water supply systems are not viable for practical and economic reasons. Specifically, the technology of fog collection has the following advantages compared to conventional means of water delivery:

6.5.1. High potential

Fog as a natural resource has the potential to supply adequate quantities of water to targeted hill communities. In areas identified as potential sites for fog-water collection, the resource is always adequate and the supply of water is limited only by the number of collectors installed in those areas [55], which in turn depends on availability of funds.

6.5.2. Cost-effective

In areas where fog-water collection is feasible, the required amount of water could be delivered to beneficiary communities in a comparatively cost-effective way compared to conventional water supply systems.

6.5.3. Simplicity

The technology of fog collection is relatively simple to implement and system operation is easy. The initial introduction of the technology might require external expertise to identify the potential sites for implementation of technology. Once the system is installed, trained community members can operate and maintain the system. Afterwards, local experts could install the technology at other potential sites.

6.5.4. Energy-free

The technology of fog collection is passive and energy-free. There are no mechanical works or energy supplies required to operate the system. Once the fog collectors and the whole water supply system are put in place, the water is conveyed to a distribution system via gravitational flow of water.

6.5.5. Marginal operational cost

Initial cost of the infrastructure might be excessive for poor communities. However, if the system is installed with all the required physical strength to withstand strong wind through government or outside assistance, the beneficiary community could operate the system with income generated from water tariffs.

6.5.6. Multipurpose

Generally the quality of fog water is good [55] and could potentially be used for domestic purposes, for establishing small-scale gardens through efficient drip irrigation systems, and for reforestation of hills that could be practically and economically difficult through other means.

6.6. Technology disadvantages

6.6.1. Localised

Fog formation needs favourable topo-climates and altitudinal gradients preferably along coastlines. Not all regions of the world have this kind of natural setting for optimum fog formation and for utilising the technology. This largely limits the use of the technology to localised mountain ranges of coastal areas.

6.6.2. Seasonal

Fog occurrence is seasonal and its duration varies within different regions of the world. Some areas have year-round fog like the north coast of western Chile while others, like Oman, have few fog periods (60 days) even though the collection rate is high ($30\ \mathrm{L\,m^{-2}\,day^{-1}}$). Therefore, in most cases, the fog-water supply becomes seasonal which forces communities to find supplementary water supply systems or incur additional storage costs for more fog water to use outside the fog period.

6.6.3. Maintenance requirement

This technology needs regular maintenance and supervision by trained members of the beneficiary community. These tasks include tightening loose cables, mending torn mesh, and, at worst, erecting collapsed meshes. If communities are not highly motivated and fully dedicated to maintaining functionality of the system, the technology might face a challenge and termination as witnessed in many countries.

7. Conclusions and recommendations

The technology of fog collection is a proven innovative method of water collection from the atmosphere and could provide water to communities where the conventional water supply systems are not viable or too expensive. Over the last years, this technology has been operational in a number of arid and semi-arid regions for purposes of domestic, agricultural and reforestation programmes. The immediate results of the technology are usually remarkable and beneficiary communities witnessed its impacts on their lives. In these countries, fog water has been demonstrated as a potential water resource to address the shortages of water. In addition, there are many countries in which the technology has been evaluated using standard fog collector (SFC) units and found to be a feasible

option. Therefore, these countries need to consider fog-water collection in their regional water supply master plans.

The amount of collected fog water is adequate in the areas where fog occurrence is continuous throughout the year. However, in other areas the fog period is not long enough for provision of water throughout the year. In such cases, the technology has to strategically enlarge its storage capacity or be supplemented with other means of water delivery such as roof-water harvesting. If the technology is used for agricultural purposes, the collected water can be used efficiently with a drip irrigation system for vegetables and fruit trees. Similarly, in reforestation programmes, the drip irrigation systems should be utilised effectively to improve the survival rate of tree seedlings. It is preferable to plant trees with needle-shaped leaves (such as coniferous trees) since these plants need support only until they reach a certain height, typically 2 m, after which they can naturally collect fog by themselves.

Fog-water quality should be considered as a part of the evaluation criteria in all fog collection projects. Generally, the collected fog-water quality, almost from all countries that tested the technology, is within an acceptable range of the WHO standard. If fog water is collected for domestic purposes and if there is a potential source of pollutants, then special care should be taken to analyse its quality. Quality of fog water stored for an extended period should be preserved through conventional means of water treatment – filtration and chlorination.

For a fog-water supply system to be successful and sustainable, equal consideration should be given to the social and cultural settings of the beneficiary community together with topographic and climatic studies. In line with installation of the technology, intensive community sensitisation and information need to be undertaken in order to develop awareness by the beneficiaries and social acceptance of the technology. As demonstrated by previous projects, the main cause for termination of fog-water supply systems was a lack of strong involvement and commitment of communities. Therefore, an implementing team has to be composed of experts with knowledge of the technical aspects about the technology as well as a sociologist/related professional to address the social and cultural aspects with the beneficiary communities. The implementation of the technology could be focused to benefit a whole village, or a section of a community such as schools or churches/temples. Recent experiences demonstrated that the technology works effectively at family level since it creates a high sense of ownership and allows for direct accountability.

Technically, fog-collection technology needs further research to address its limitations. Mainly, the technology requires an alternative mesh type for windy areas. The polypropylene or polyethylene mesh type, which is used in most fog collection projects worldwide, is not robust enough to withstand strong wind as witnessed in some countries. Its physical weakness jeopardises operation of the system and could ultimately influence the trust of a beneficiary community in the technology. In order to mitigate this technical drawback, the ongoing research on manufacturing a robust mesh type needs to be intensified to find a standard mesh type which is robust enough to endure strong winds and the harsh environment of arid lands in general and increased ultraviolet radiation in high altitude locations. In addition, the technology requires a regular follow-up to tighten the supporting cables. These measures might be challenging for a subsistence community and thus solid craftsmanship needs to be adopted in order to cope with this extra work.

The technology of fog collection needs time and close follow-up until beneficiary communities are able to adopt and operate the system in a sustainable manner. Therefore, an effective local implementing partner (government body or non-governmental organisations) should be in place in order to assist the community technically and if need be financially as well. The local partner has to be committed for a long period of time after the system is handed over to the community. Structurally, the community water committee has to be linked to this local partner for occasional backstopping when the community needs intervention which is beyond their means.

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